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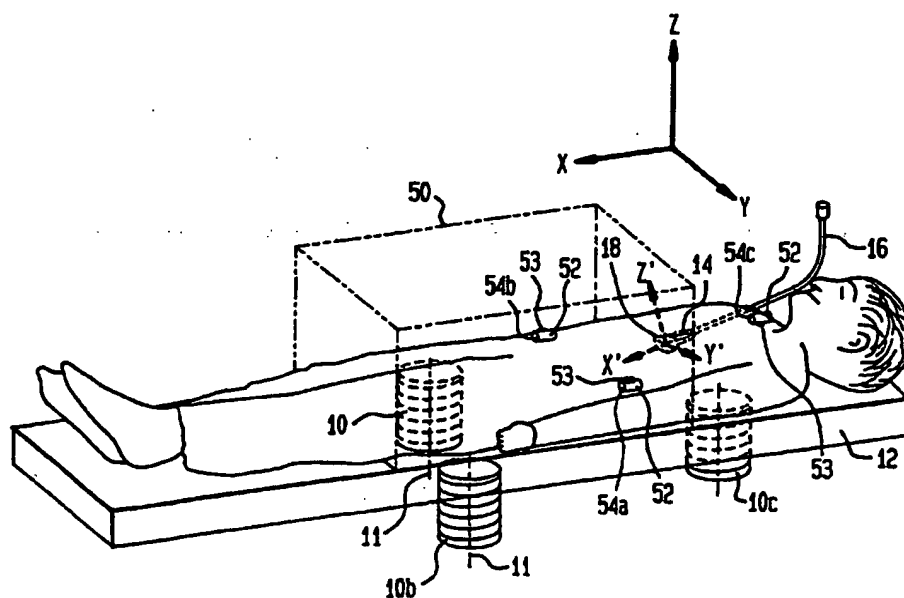
(57) Abstract

A system for locating objects in space, such as medical instruments (16) within the body of a patient (P), based upon transmission of magnetic fields from coils (10) in a fixed frame of reference to sensors (20, 22, 24) on the object or vice-versa. The current supplied to the coils is adjusted to assure that the sensors receive fields within a preselected range of magnitudes regardless of the location of the object in space. This assures that the sensor operates within its optimum range, and permits use of compact transmitters and sensors.

DESCRIPTION

MAGNETIC LOCATION SYSTEM
WITH ADAPTIVE FEEDBACK CONTROL

TECHNICAL FIELD

The present invention relates to systems for determining the location and/or orientation of objects in space by detecting magnetic fields.

BACKGROUND ART

Various systems have been proposed for detecting the position and/or orientation of an object using magnetic or electromagnetic fields. These systems typically employ field transmitters, such as electromagnet coils, disposed at known locations in a fixed reference frame and a sensor, such as a coil or other transducer mounted to the object to be located. Each transmitter projects a field varying in space in a fixed frame of reference. The pattern of variation in space for each transmitter is different than the pattern for each other transmitter. For example the transmitters may be identical to one another but disposed at different locations or in different orientations. The field patterns of the transmitters are thus displaced or rotated relative to one another and relative to the fixed frame of reference. The sensor on the object detects the parameters of the field prevailing at the location of the object as, for example, the magnitude and/or direction of the field at the object or the magnitudes of individual components of the field at the object in one or more preselected directions. The transmitters may be actuated in a predetermined sequence so that at any time only one transmitter is active and therefore the field prevailing at the object is only the field contributed by one transmitter, plus a background field due to the Earth's magnetic field and other environmental sources. Alternatively, the transmitters can be driven at different frequencies so that components of the signal

from the sensor varying at different frequencies represent contributions to the field at the object from different transmitters. Based upon the detected parameters of the fields from the individual transmitters, and the known pattern of variation of the field from each transmitter, a computer system calculates the position and orientation of the sensor, and hence the position of the object bearing the sensor, in the fixed frame of reference of the transmitters. In a variant of this system, the object to be located carries the transmitter or transmitters, whereas a plurality of sensors are disposed at various locations or orientations in the fixed frame of reference. The location and/or orientation of the object is deduced from signals representing the parameters of the field prevailing at the various sensors.

Systems of this general nature are disclosed in United States Patents 4,849,692; 4,642,786; 4,710,708; 4,613,866 and 4,945,305. Systems according to this general design can be used to provide a three-dimensional spatial input capability for a computer. Another system of this nature is disclosed in International Patent publication WO94/04938. In the '938 publication, the object to be located may be a medical endoscope. Such a system may include a sensor mounted on the tip of an endoscope, so that the location and/or orientation of the endoscope tip can be determined while the sensor is disposed inside the body of a medical patient. This allows the physician to monitor the endoscopic procedure without resorting to a fluoroscopy or other techniques using ionizing radiation to localize the instrument. In one embodiment (pages 26-27), the '938 publication contemplates an arrangement in which plural transmitting coils are actuated simultaneously to "steer" the direction of the resulting field and thereby align the field with the sensor. The '938 publication characterizes this arrangement as undesirable. Other systems for locating medical

instruments such as endoscopes and catheters based upon
transmitted fields are disclosed in United States Patent
No.   5,042,486;   5,099,845;   5,211,165;   5,251,635;
5,253,647; 5,255,680; 5,265,610 and 5,391,199.

Systems of this nature typically have used
fields having strength which varies as the third power,
or a higher power, of distance from the transmitter.
There is, accordingly, a very large variation in the
strength of each field from location to location. In a
medical device locating system, adapted to detect the
location of the sensor anywhere within a sensing volume
having dimensions on the order of 0.5 to 1.0 m, the
field strength may vary through many orders of magnitude
from one end of the sensing volume to another. When the
sensor and the object to be located happen to be near a
particular transmitter, they will receive an extremely
strong field, whereas when the sensor and object are at
the end of the sensing volume remote from the particular
transmitter, they will receive only a very weak field
from that transmitter. This requires a sensor with a
very substantial dynamic range, capable of accurately
monitoring very strong and very weak fields. That, in
turn, poses stringent demands on the design of the
sensor and may require a larger sensor. Moreover, the
signal to noise ratio is poor when monitoring a very
weak field and the accuracy of the system is accordingly
less than optimum in these conditions. Both of these
considerations are particularly important in systems for
medical applications, where the sensor must be small to
fit inside a medical device such as a catheter or
endoscope. Although such systems can provide useful
results, further improvement would be desirable. The
same problems arise in systems using a coil or other
transmitter on the object to be located and plural
sensors in the fixed frame of reference. Here again, a
particular sensor will be exposed either to a very
strong field or a very weak field depending on whether

the transmitter is adjacent to or remote from the sensor in question.

Commonly assigned, copending United States Patent 08/132,479 discloses a solution to these problems. Certain preferred embodiments according to the '479 application include electromagnets which are operable to generate a plurality of different magnetic fields. Each field has at least one component with a non-zero magnitude that is either constant, linear or nearly linear with respect to distance in a particular direction within a sensing volume. Such an arrangement provides less variation in field magnitude throughout the sensing volume than a comparable arrangement in which the field strength varies as the third or higher power of distance. Thus, with the quasi-linear fields, the difference between minimum and maximum field within a given sensing volume is substantially smaller. This substantially alleviates the problems discussed above. However, it is not always convenient to use the particular coil arrangements which provide such quasi-linearly varying fields.

SUMMARY OF THE INVENTION

One aspect of the present invention provides apparatus for determining position including field generating means for producing a plurality of magnetic fields. The field generating means is arranged to provide such fields having parameters, such as field strength and/or field direction, varying with location within a sensing volume according to known patterns of variation. The pattern of variation for each field is different than the pattern of variation for each other field. For example, where the field generating means includes a plurality of transmitting coils, the coils are disposed at different locations and/or different orientations relative to the sensing volume. Apparatus according to this aspect of the invention also includes at least one sensor adapted to detect one or more parameters of the field prevailing at the sensor when

the sensor is at an unknown location within the sensing
volume, and to provide one or more sensor signals
representing such detected parameters. For example, the
sensor may include a sensor body and a plurality of
component sensors disposed on the sensor body, each
component sensor being operative to measure the
magnitude of a magnetic field component in a preselected
local direction relative to the sensor body to provide a
component sensor signal representing that particular
component of the field prevailing at the sensor. The
apparatus further includes calculation means for
calculating the location of the sensor, the orientation
of the sensor or both based upon the sensor signals and
upon the unknown patterns of variation of the fields.
The apparatus also includes feedback control means for
adjusting the field generating means to alter the known
pattern of variation of at least one of the fields
responsive to the sensor signals, to the calculated
location of the sensor or both so as to maintain the
detected parameters of the altered field at the sensor
within a preselected range. For example, where the
field generating means includes a plurality of
transmitters disposed adjacent the sensing volume, the
feedback control means can be arranged to increase the
strength of the field transmitted by a particular
transmitter when the sensor is remote from such
transmitter, and to decrease the strength of the field
emitted by that transmitter when the sensor is close to
the transmitter. Thus, the parameters of the field
detected at the location of the sensor will always lie
within a relatively narrow range of values. Because the
transmitted field is altered in a known manner, the
position and/or orientation of the sensor can still be
calculated, simply by using the altered field as the
basis for calculation. For example, where the feedback
control means increases the current flowing to an
electromagnetic coil, the parameters used in the
calculation to represent the strength of the field

emitted from that particular coil are adjusted accordingly.

Apparatus according to this aspect of the present invention can maintain the detected field parameters at the sensor location, such as the magnitude of the field at such location, within a relatively narrow range even where the field strength varies with a power of distance greater than the first power as, for example, where the field strength varies with the third power of distance from the coil. The system therefore can provide good signal to noise ratio, even with a very small sensor. Moreover, there is no need for any particular coil configuration to produce a linear or quasi-linear field. For example, in a medical application, a plurality of individual coils may be disclosed at various locations beneath a patient receiving bed, or on one side of the bed.

Although apparatus according to this aspect of the invention can utilize any type of sensor, it has additional advantages when used with magnetoresistive sensors or other sensors which can lose accuracy when exposed to very high magnetic fields. Because the field is maintained within a relatively narrow range, the sensors are not exposed to fields which would impair their accuracy. In a further variant of the invention, the feedback control system is actuated to maintain the parameters of the field at each sensor within the narrowest attainable range of values. Thus, the feedback control maintains the field parameters at the sensor at substantially constant values. Here again, the transmitted fields are altered in a known manner, and the disposition of the sensor can still be calculated by using the altered fields as the basis for calculation.

A further aspect of the present invention provides apparatus including at least one transmitter adapted for mounting to the object to be located and also including a plurality of sensors disposed adjacent

a sensing volume. The apparatus according to this aspect of the invention includes calculation means for determining a calculated location of the transmitter based upon signals from the sensors and upon the known pattern of variation of the field at the transmitter. Here again, feedback control means are provided for adjusting the field generating means to alter the known pattern of variation of field sent by the at least one transmitter in response to the sensor signal, to the calculated location of the transmitter or both so as to maintain the parameters of the field from the at least one transmitter prevailing at each sensor within a preselected range. This arrangement is similar to the arrangement discussed above, except that the transmitter or transmitters are disposed on the object to be located whereas the sensors are located in the fixed frame of reference of the sensing volume. Here again, when the transmitter is close to the sensor, or where the orientations of the transmitter and sensor favor strong coupling between the transmitted field and the sensor, the strength of the field is reduced. If the transmitter is relatively far from the sensor, or in a unfavorable orientation, the control means increases the strength of the transmitted field. This arrangement provides advantages similar to those discussed above.

A further aspect of the invention provides apparatus for sensing the disposition of an object--its position, orientation or both--in a frame of reference. Apparatus according to this aspect of the invention includes transmitter means including at least one transmitter for providing a field and sensor means including at least one sensor for sensing one or more parameters of a field prevailing at each such sensor and providing one or more sensor signals indicative of such parameters. The transmitter means and said sensor means cooperatively define a plurality of transmitter-sensor pairs, each including one transmitter and one sensor as elements of the pair, one element of each such pair

being disposed on the object and the other element of each such pair being disposed at a known disposition in said frame of reference. Typically, at least one element of each transmitter-sensor pair is disposed at a different position or orientation than the corresponding element of the other pairs. The apparatus further includes calculation means for determining the disposition of said object based upon said sensor signals feedback control means for adjusting said transmitting means responsive to said sensor signals to thereby maintain at least one of said sensor signals within a preselected range.

Further aspects of the present invention provide methods of determining position and/or orientation wherein the operation of field generating means is altered by feedback control based upon the signals from the sensor, or from the calculated location of the sensor of the transmitter, to maintain the parameters of each field to be detected by each sensor within a preselected range.

Other objects, features and advantages of the present invention will be more readily apparent from the detailed description of the preferred embodiments set forth below, taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a diagrammatic prospective view depicting portions of apparatus in accordance with one embodiment of the invention.

Figure 2 is a fragmentary, diagrammatic prospective view depicting a portion of the apparatus illustrated in Fig. 1.

Figure 3 is a functional block diagram depicting further portions of the apparatus depicted in Figs. 1 and 2.

Figure 4 is a block diagram depicting certain steps in methods according to embodiments of the invention. Figures 5 and 6 are a diagrammatic

perspective view depicting portions of apparatus in accordance with a further embodiment of the invention.

BEST MODE OF CARRYING OUT INVENTION

Apparatus in accordance with one embodiment of the present invention includes three generally helical transmitter coils 10 disposed in a common plane. Coils 10 are mounted in fixed position in the frame of reference of patient receiving bed 12. That frame of reference is denoted by a Cartesian coordinate system X, Y, Z as shown in Fig. 1. A patient P may be positioned on the patient receiving bed. The axes 11 of the coils are parallel to one another. A patient receiving bed 12 extends just above the plane of coil 10. The apparatus further includes an object or probe 14. The probe is adapted to be inserted into a medical instrument such as a catheter 16 and positioned at a desired location in the catheter, such as at the distal tip of the catheter or at another location along the length of the catheter. Probe 14 has mounted thereon a sensor 18. Sensor 18 includes three component sensors 20, 22 and 24 adapted to sense components of the magnetic field in mutually orthogonal local directions X', Y' and Z'. That is, component sensor 20 is sensitive to magnetic fields directed in direction X', but largely insensitive to fields in directions Y' and Z', whereas sensor 22 is sensitive only to fields in direction Y' and sensor 24 is sensitive to fields in direction Z'. These sensors are adapted to provide separate sensor signals representing the separate components. Sensor 18 may be a solid state sensor of the type described in the aforementioned International Patent Publication WO95/09562, the disclosure of which is hereby incorporated by reference herein. As further described therein, each of the component sensors may include a generally planar magnetically sensitive film, such as a magneto-resistive film or a Hall effect sensing film. Each such film may be sensitive to fields directed normal to the plane of the film. Alternatively, sensor

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18 may include an array of miniature coils, the axes of the coils being oriented orthogonal to one another. Although these represent the preferred sensors, essentially any other magnetically sensitive device may be employed as, for example, magneto-optical sensors and flux gate magnetometers.

Component sensors 20, 22 and 24 are connected through a cable 26, with separate leads for each sensor, to a command unit 28. Command unit 28 (Fig. 3) includes an input amplification and analog to digital ("A/D") conversion section 30 adapted to receive the individual signals from component sensors 20, 22 and 24 of sensor 18, amplify the same and convert the same to digital form. The amplification and A/D conversion unit 30 may also include other conventional signal processing devices such as analog or digital band pass filtering and noise rejection devices and signal averagers. Command unit 28 further includes a computation unit 32. Computation unit 32 may be implemented as a programmed general purpose computer. As further discussed below, the position computation unit is arranged to compute the disposition of sensor 18, and hence the disposition of the object or probe 14 at the catheter tip from the sensor signals. As used in this disclosure, the term "disposition" of an element refers to the position of the element, the orientation of the element or both. Thus, the computation unit is arranged to calculate the position of sensor 18, the orientation of the sensor, or, preferably, both position and orientation. Command unit 28 may be linked to a display device (not shown) for providing a human intelligible representation of the position of the probe or object 14. Such human intelligible representation may be provided either as numerical information presenting the position and/or orientation of object 14 in the X, Y, Z coordinate system or, preferably, as a pictorial representation of the object and of the associated catheter superposed on a pictorial representation of the patient .

Command unit 28 further includes a control
unit 34. Control unit 34 is linked by output lines 36,
38 and 40 to three separate coil drivers 42, 44 and 46.
Each coil driver is linked to a separate one of
transmitter coils 10. Each coil driver is adapted to
send a direct current through the associated transmit
coil 10. Each coil driver is arranged to control the
amplitude of such current, and to turn the current on or
off, in response to control signals received from
control unit 34. The control unit is arranged to signal
the coil drivers to provide currents to their respective
transmit coils in alternating sequence, so that coil 10a
receives current while coils 10b and 10c are inactive;
coil 10b receives current while coils 10a and 10c are
inactive and coil 10c receives current while coils 10a
and 10b are inactive. The control unit receives data
from amplification and conversion section 30 and, as
further discussed below, actuates the coil drivers to
vary the amplitude of the current to each coil. The
control unit may include conventional interface devices
such as digital to analog converters or bus interface
units so that the output of the control unit is
compatible with the control input of each coil driver.
Also, although the control unit is illustrated
separately from the other logical units of command unit
28, it should be appreciated that the control unit may
share physical elements of the command unit and other
elements. For example, where the command unit
incorporates a general purpose computer, the processor
of the computer may serve both as an element of the
position computation unit and as an element of the
control unit, executing functions appropriate to the
different units at different times.

In a method according to one aspect of the
invention, an catheter 16 is advanced into the body of a
patient P. The probe 14 with sensor 18 thereon is
disposed at the tip of the catheter. The catheter tip
is disposed at an unknown location somewhere above the

plane of coils 10. Control unit 34 actuates the coil drivers in sequence, using an initial or default value for the current amplitude to be provided to each coil 10. Amplification and conversion unit 30 samples the signal from each of the component sensors 20, 22 and 24 at a preselected time after the beginning of current flow through each coil. For example, at a preselected time after the beginning of current flow through transmit coil 10a, unit 30 takes a sample of the signal from each of component sensors 20, 22 and 24, and converts the same to digital format. Command unit 28 then calculates a total field magnitude based upon these individual signals. The total field magnitude is:

$$|B_{10a}| = \sqrt{(k_{20}S_{20})^2 + (k_{22}S_{22})^2 + (k_{24}S_{24})^2}$$

where: B_{10a} is the magnitude of the magnetic field vector at sensor 18 at the time that coil 10a is actuated;

K_{20} is a sensitivity factor relating the signal strength from sensor 20 to the magnetic field component along axis X';

S_{20} is the signal strength from sensor 20 during the actuation; and

K_{22}, S_{22} and K_{24} and S_{24} are similar sensitivity constants and signal strengths for the other sensors 22 and 24.

In like manner, the system actuates coils 10b and 10c in order, using the default current strength. Here again, the system computes the magnitude of the total field vector prevailing at the sensor during actuation of coil 10b and independently computes the magnitude of the total field vector prevailing at the sensor during actuation of coil 10c.

As shown in Fig. 4, after detecting the component signals and calculating the total field magnitude prevailing at the sensor during actuation of each coil, the control unit determines whether or not

all of the field magnitudes are within a preselected
range of magnitudes. This preselected range is chosen
to lie within the optimum operating range of sensor 18.
Thus, the minimum field magnitude is selected to lie
5   well above the noise threshold of the system and above
the minimum sensitivity level of the sensor, where the
maximum field level is selected to lie well below the
maximum limit of linearity of the sensor, and well below
the maximum field which the sensor can tolerate without
10   loss of accuracy. For a typical magneto-resistive
sensor, which is most accurate and repeatable when used
with fields of less than about 4 Gauss, the preselected
range of field magnitudes may be from about 1.0 to about
2.5 Gauss. With typical Hall effect sensors, which are
15   most accurate when used with fields over about 30 Gauss,
the preselected range will be above about 30 Gauss. If
the three field vector magnitudes observed during
actuation of the three units 10a, 10b and 10c all lie
within the preselected range, than the system proceeds
20   to calculate the position and orientation of sensor 18,
and hence the position and orientation of probe 14 and
the associated tip 16 of the catheter using conventional
position finding algorithms. For example, the
mathematical methods disclosed in United States Patent
25   4,710,708 for finding positions using a multiple
transmitting or receiving stations and a multi-axis
sensor can be employed. The disclosure of said '708
patent is hereby incorporated by reference herein.
Briefly, the magnitude of the fields in each of the
30   local or sensor directions X', Y', Z' represented by
each of the component sensor signals from each of the
component sensors 20, 22 and 24 is a function of the
overall strength of the field from the coil (also
referred to as the magnetic dipole moment of the coil),
35   the distance from the particular coil to the sensor and
the sensor rotation angles, i.e., the angles between the
local directions X', Y' and Z' and the coil frame of
reference directions X, Y and Z. When three component

sensor readings are collected during actuation of three separate coils and equated with the component strength, expressed as a function of location for fields from a particular coil, they form a system of nine equations with six unknowns (the X, Y, Z location of the sensor and the three rotation angles). The derivation of these equations is set forth in Appendix A. That system of equations can be solved by iterative methods such as the method of Marquardt or the method of Broyden for least-squares solution of an overdetermined system of nonlinear equations. The command unit then provides output indicating the position and orientation of the sensor and hence indicating the position and orientation of probe 14 and of the distal tip of the catheter.

If one or more of the field magnitudes is out of the preselected range, the system does not calculate the position and orientation. Instead, control unit 34 changes the field strength of the coil or coils associated with the out-of-range field strength. For example, where probe 14 and sensor 18 are relatively close to coil 10a, the total field magnitude detected when coil 10a is actuated will be above the preselected range. Control unit 34 therefore will command coil driver 42 to reduce the current to coil 10a on the next actuation cycle. Conversely, if the probe and sensor are relatively far from coil 10c, the field magnitude sensed during actuation of coil 10c with the default of current value will be below the preselected range. Control unit 34 therefore will instruct coil driver 46 to increase the current to coil 10c on the next actuation cycle. The coil drivers may be arranged to vary the overall field strength or dipole moment of each coil stepwise, as by varying the current stepwise. Each increase or decrease commanded by control unit 34 may be one step. Alternatively, the control unit can calculate an increase or decrease proportional to the degree to which the total field magnitude deviates from a target value within the preselected range. Thus, a relatively

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large change can be made when the field magnitude is far outside of the range, whereas a smaller change can be employed when the field magnitude is close to the range or within the range. The correction process continues until all field strengths are within the preselected range, whereupon the system calculates position and orientation. After the system finds values of coil currents which produce field magnitudes within the range, subsequent actuation cycles use these currents. During operation, as the physician utilizes catheter 16, the position of the catheter tip, and hence the position of probe 14 and sensor 18 may change. Any such change may bring one or more of the field magnitudes outside of the preselected range, whereupon the system will readjust the currents to the coils once again.

As the feedback control unit readjusts the currents to the coils, the altered values of current are translated into new values for field strengths from the individual coils which are used in the aforementioned position determining equations. In this manner, the system assures that the sensor is always exposed to a field having a magnitude within the preselected range wherever the sensor is placed within a sensing volume 50 extending over a preselected region above the plane of coils 10. The exact size of sensing volume 50 will depend upon the breadth of the preselected field magnitude range and the dynamic range of coil drivers 42, 44 and 46, i.e., the degree to which the coil drivers can vary the currents. The size of sensing volume 50 within which the sensor will receive fields within the preselected field magnitude range from all coils will also depend upon the positions of the coils. However, for a typical system having three coils spaced at vertices of an equilateral triangle with sides about 40 cm long, the sensing volume includes a region extending upwardly about 60 cm from the plane of the coils. At the plane of the coils, the sensing volume

extends about 20 cm beyond the equilateral triangle bounded by the coils.

In the description set forth above, only one sensor is employed to determine the position and location of only one object. However, plural objects and plural sensors may be utilized. As described in the aforementioned International Publication WO95/09562, a plurality of fiducial markers may be utilized. Each fiducial marker may include a sensor body 52, a tag 53 and a sensor 54 of the same type as sensor 18 releasably connected to the sensor body. The amplification and converson unit 30 is connected to each of these additional sensors in the same manner as to sensor 18. The tag of each sensor may be affixed to the body of the patient, and an image of the patient may be acquired using any imaging method which will show the desired structures of the patient's body and which will also show the tags 53 as, for example, magnetic resonance imaging (MRI), X-ray, CAT scanning or the like. Thus, the tags are constructed to facilitate imaging in the desired imaging method. Where X-ray imaging is used, the tag may be radioopaque; where MRI imaging is used, the tag may include a material which has magnetic resonance response readily distinguishable from that of bodily tissue. Ordinarily, the image is acquired prior to use of the catheter and probe discussed above. The sensors 54 typically are not present in the imaging step. After the imaging step, the sensor bodies 54 and sensors of the fiducial markers are attached to the patient's body at the positions of the tags. When the catheter is employed, sensor signals from sensor 18 on the probe in the catheter are acquired concurrently with signals from the sensor 52 on the fiducial markers. The system determines the location and orientation of sensor 54, and hence of fiducial markers 52 using magnetic fields from coils 10 in the same manner as the system determines the position and orientation of sensor 18 and probe 14. The acquired position and orientation of the

fiducial markers 52 can be used to register the
previously acquired image of the patient with the
position and orientation data for sensor 18 and probe
14. For example, where the position and orientation
5   data for the sensor 18 and probe 14 are displayed as a
pictorial image of the catheter tip 16 on a screen, the
position and orientation of fiducial markers, as
determined by the magnetic field locating method can
also be displayed. The previously acquired image data
10   may be displayed as a pictorial representation of the
patient's structures and that representation will also
include a picture of the tags 53. The previously
acquired images   of the tags are brought into
registration with the images of the fiducial markers
15   derived from magnetic location by transforming one or
the other image until the picture of the tags in the
previously acquired image overlies the representation of
the fiducial marker in the magnetically acquired image.
Such registration can be achieved by manually adjusting
20   inputs to an image display system while visually
matching the displayed images, as described in the
aforementioned `562 International Publication. or else
by automatic calculation of the transformation and
rotation parameters necessary to bring the images into
25   registration. Such parameters can be calculated by
equating the positions of three or more fiducial marker
sensors in the magnetic location frame of reference (the
X,Y,Z coordinates of Fig. 1) with the positions of the
tags 53 in the image frame of reference as modified by
30   a matrix of unknown rotations a further matrix of
unknown transformations. As further described in
Appendix B, the resulting matrix equation yields an
overdetermined system of nonlinear equations which
include the rotation angles and transformation
35   distances. When the images are properly registered, the
position of the catheter tip is displayed in true
location and orientation relative to the patient's
internal structures. In similar fashion, a greater

number of fiducial markers, or more than one medical instrument may be located.

In a system using multiple sensors, such as sensors 18 and 54, the coils may be operated in separate cycles so as to provide each sensor with fields having magnitudes in the preselected range appropriate for the sensor. For example, control unit 34 may actuate the coil drivers 42, 44 and 46, and hence transmitting coils 10, in first, second, third and fourth cycles. During the first cycle, the signals from sensor 18 are acquired and the signals from sensors 54 of the fiducial markers are ignored. During the first cycle, the coil currently is adjusted to yield field magnitudes at sensor 18 within the preselected range as discussed above. During the second cycle, the signals from the sensor 54a of a first fiducial marker are acquired, the signals from sensor 18 and the other fiducial marker sensors 54b, 54c are ignored and the coil currents are adjusted to provide a field magnitude at sensor 54a within its preselected range. In the third cycle, the signals from sensor 54b are acquired whereas the other signals are ignore; in the fourth cycle, the signals from sensor 54c are acquired and others are ignored. The cycles may be sequential, with the entirety of a first cycle being performed before the entirety of a second cycle. The cycles may also be interspersed with one another. For example, coil driver 42 can be actuated first to provide a current appropriate to yield the proper field at the first sensor 18 and then can be actuated to provide the appropriate fields at the fiducial marker sensors 54a, 54b and 54c in succession, followed by a similar multiple actuation of the other coils. Likewise, where more sensors are employed, there may be as many separate cycles of operation as sensors. Alternatively, if some of the sensors are known to be close to one another, or if the data from some sensors is less critical than the data from other sensors, the number of cycles may be less than the number of sensors. Thus, the currents

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used on a given cycle may be adjusted to provide fields within the desired range of magnitude for one sensor. Signals from other sensor can be acquired during this cycle, although such other sensor may encounter a field outside the preselected range. In some cases, the coil currents are fixed for some cycles and adjusted for others. For example, where numerous fiducial markers are employed, it may be possible to achieve acceptable registration accuracy using fixed coil currents to provide the fields when data is acquired from the fiducial markers, whereas the coil currents may be adjusted in the manner discussed above when data is acquired from the sensor in the active device or catheter.

Certain sensors tend to lose accuracy when exposed to magnetic fields above a predetermined maximum. For example, certain magneto-resistive sensors temporarily lose accuracy if exposed to magnetic fields above about 4 Gauss. Where such sensors are employed in a multi-sensor system, the system should have appropriate provisions to avoid exposing sensors to excessive fields. For example, if sensor 54a is disposed close to coil 10b, whereas sensor 18 is disposed remote from coil 10b, sensor 54a may be exposed to extremely high field levels if the system adjusts the current in coil 10b to the level required to generate the appropriate field at sensor 18. To avoid this condition, the data from all sensors can be acquired during all of the cycles, and control unit 34 can be arranged to increase coil currents in a progressive manner over several cycles when an increase is required. The data from sensors which are not used for position monitoring on a particular cycle can be used to inhibit further increases if the field at the nominally unused sensor is approaching dangerous levels. Thus, if the system is in the process of progressively increasing the coil current in coil 10b to provide an adequate field level at sensor 18, the system may terminate such

increases if the field magnitude at second sensor 54a during the reading cycle associated with first sensor 18 reaches the maximum level allowed at the second sensor. If this condition occurs while the field level at first sensor 18 is still below the preselected range, the system may display an error message or else may attempt to calculate position and orientation based on out-of-range sensor signal, or both. Alternatively, if the accuracy of the sensor can be restored, the data from the nominally unused sensors can be used to initiate restoration. For example, certain magnetoresistive sensors use a biasing magnetic field. If exposed to excessive fields, such sensors can be reset and restored to accuracy after the excess field is removed by adjusting a bias magnetic field applied within the sensor. The command unit may be arranged to trigger the reset process for one sensor if it is exposed to excess field during a cycle associated with another sensor.

In the foregoing discussion, the coils are driven alternately in a time-multiplexed arrangement. Frequency domain multiplexing can also be employed. Thus, each coil can be actuated with a driving current having a different carrier frequency, and such actuation can be substantially continuous. The signals from sensor 18 will include components varying at the different carrier frequencies, which can be segregated by analog or digital filtering methods. Thus, the signals from component sensor 20, 22 and 24 varying at the carrier frequency of coil 10a can be used to calculate the total field magnitude attributable to coil 10a. That value in turn can be used to trigger feedback control unit 34 to adjust the current to coil 10a. The currents in the other coils can be adjusted in similar manner using the components varying at their respective carrier frequencies. The frequency division multiplexing approach can be extended to multiple sensors. For example, each coil can be driven at a

multiple carrier frequencies, equal to the number of
sensors, the carrier frequencies for each coil being
different from one another and different from all of the
other carrier frequencies for all of the other coils.
The components in the signals from the first sensor
varying at the respective first carrier frequencies can
be detected and the strength of the coil currents at the
respective first carrier frequencies can be adjusted
accordingly, so that the field magnitudes at the first
carrier frequencies prevailing at sensor 18 will be
within the desired range. In this stage of the process,
the components varying at the other carrier frequencies
are ignored. The process is reversed with respect the
fiducial marker sensor 54a. This approach can be
extended to greater numbers of sensors. Also, the
frequency multiplexing and time multiplexing approaches
can be combined. Thus, each coil can be driven at only
one carrier frequency. During a first cycle, first
sensor 18 is actuated and the components varying at all
of the carrier frequencies are monitored. The coil
currents are adjusted accordingly to bring the fields at
each carrier frequency into the desired range. During a
second cycle, the second sensor 54a (the first fiducial
marker sensor) is used and the coil currents are
adjusted in the same manner, and so on with the other
fiducial marker sensors.

In a further variant, the coil currents, and
hence the strengths of the fields from the individual
transmitters, can be adjusted to bring the field
components detected by each individual component sensor
to within a preselected range. In such a system, each
coil is adjusted separately with respect to each
component sensor. In a first cycle, the current to
transmit coil 10a is adjusted to bring the individual
sensor signal from component sensor 20, representing the
field component magnitude in the local X' direction,
into a preselected range. During this cycle, the
signals from the other component sensors 22 and 24 are

disregarded. In the next cycle, coil 10a is readjusted to bring the field component in the wide prime direction into a preselected range and thus bring the signal from Y prime direction component sensor 22 into the optimum range. The same coil 10a then brings the field component in local direction Z' into a preselected range, and the signal from the prime direction component section 24 is monitored. This sequence of operations is then repeated again for each of the other transmitter coils. This approach can be extended to plural sensors, each having plural component sensors. Here again, the system keeps track of the coil current magnitudes used to produce the fields since by each component sensor. The coil current is reflected in the coil dipole moment (overall field strength) terms of the simultaneous equations.

Where the local direction associated with a particular component sensor is orthogonal, or nearly orthogonal, to the direction of the field produced by a particular coil at the sensor, it may be impossible to bring the component in that local direction into the preselected range without either exceeding the current capacity of the coil driver or producing a total field so strong as to impair one of the other sensors. In this instance, however, at least one of the other component sensors will receive a component having a magnitude in the preselected range of magnitudes. In this variant, the signal from all of the component sensors may be monitored during a cycle associated with a particular component sensor. The maximum current applied to the coil may be limited to avoid exposing any other unused component sensor to an excessive field component in its sensing direction.

In a further variant of this approach, the preselected range of magnitudes for the field component in any particular direction is narrowed to include only a single preselected value, preferably within the optimum range of accuracy of the particular component

sensor. The feedback control system thus operates to adjust the coil currents until the field component magnitude is at such single value. The position and orientation are calculated in the same way as discussed above. This variant has the advantage that nonlinearity in the component sensor response cannot affect the accuracy of the system. Provided that it is known that a particular reading from the sensor corresponds to the preselected value of field component magnitude, deviation from a linear relationship between component magnitude and sensor reading at other values of the component magnitude will not impair the accuracy of the system.

Certain field sensors exhibit so-called "off-axis sensitivity". That is, the transfer function or relationship between field component magnitude along the sensitive axis of a particular component sensor and the reading from that component sensor varies when a strong field component orthogonal to such axis is present. Off-axis sensitivity can be corrected by using the readings from two component sensors to evaluate the magnitude of the field perpendicular to the sensitive axis of the third component sensor, and using that magnitude to determine a correction factor to be applied to the reading from the third component sensor.

In the system described above, when the coils are driven with direct current, amplification and conversion unit 30 samples the data from each component sensor at a preselected delay time after the inception of the current. In a variant of this system, the command unit adjusts the delay time from inception of the current to sampling depending upon the current applied in a particular actuation. After inception of the current, the current gradually rises to its steady state value, and hence the overall field strength or dipole moment likewise rises gradually. The changing field induces eddy currents in electrically conductive materials which may be present in or near the sensing

volume. These currents induce additional magnetic fields, which can induce erroneous sensor readings. The eddy currents decay when the rate of change in the field slows, as the field approaches its steady state value. The delay time should be long enough for the current to rise to an appreciable portion of its steady state value, and long enough for eddy currents to dissipate sufficiently that they do not cause appreciable errors. The required delay time is less with smaller field magnitudes.

The system illustrated schematically in Figs. 5 and 6 is similar to that discussed above, except that the roles of the transmitter and sensors are reversed. That is, the probe or object 114 to be tracked is equipped with a transmitters 118 incorporating three miniature coils 120, 122 and 124 disposed on mutually orthogonal axes. These are linked to a control system and coil drivers (not shown) similar to those discussed above with reference to Fig. 3. The fixed reference frame system has three undirectional sensors 110a, 110b and 110c mounted in fixed position relative to the patient receiving bed 112. The sensors are mounted in a common plane. The common plane of the sensors extends generally vertically on one side of the patient receiving bed. The sensing volume 150 extends outwardly from the common plane of the sensors, above the patient receiving bed.

This system can be used in essentially the same manner as the system discussed above. Here again, the current delivered to each coil, and hence the dipole moment of the transmitted field associated with each coil is adjusted so that the magnitude of the field component in the sensing direction of each sensor prevailing at each sensor is within a preselected range of magnitudes.

Numerous combinations and variations of the features discussed above can be utilized without departing from the present invention. By way of

example, the transmitting coils 10 of Fig. 1 can be
disposed in a vertical plane arrangement as illustrated
for the sensors in Fig. 5. Also, the number of
transmitters and sensors can be varied. For example, as
disclosed in the aforementioned International
Publication WO94/04938, the system may include a sensor
having three mutually orthogonal sensing axes and a set
of three mutually orthogonal transmitting coils having a
common center in the fixed frame of reference.
Alternatively, the system may include a single uniaxial
transmitting coil on the object to be located and three
sets of sensors on the affixed frame of reference, each
such sensor set incorporating three receiving coils or
component sensors adapted to detect fields in a mutually
orthogonal direction. The reciprocal arrangement --
with three sets of mutually orthogonal transmitting
coils and a single uniaxial sensor on the object to be
tracked -- is also usable. In general, the sensors and
transmitters should define a plurality of transmitter-
receiver pairs, each including one element on the object
and one element on the fixed frame of reference.

In a further variant, the system adjusts the
output of the transmitters in response to the calculated
disposition of the object being tracked, rather than
directly in response to the component signals or total
field magnitude signal. Thus, the system can initially
operate with the default of current values; derive an
initial reading of the position and orientation of the
object and then use that initially determined position
and orientation to calculate the desired setting for
each coil to achieve the desired field levels at the
sensor. Such desired setting is selected to yield the
field within the desired magnitude range at the object,
assuming that the object has the position and
orientation found in the initial reading. On the next
cycle, the so-calculated coil currents are utilized and
the process is repeated. In a variant of this approach,
the system can store a lookup table listing the

appropriate coil currents for various combinations of object position and orientation. Using the initially determined position and orientation, the system retrieves appropriate coil-current values from the lookup table for use in the next cycle.

In the embodiments discussed above, the sensor is associated with a catheter. The same system can be used with other medical instruments as, for example, endoscopes and surgical instruments. The system can also be applied to determine the disposition of objects other than medical instruments. For example, it can be used in tracking an input device for a computer.

As these and other variations and combinations of the features described above can be utilized without departing from the invention, the foregoing description of the preferred embodiments should be taken by way of illustration rather than by way of limitation of the invention as defined by the claims.

INDUSTRIAL APPLICABILITY

The invention can be applied in the medical and surgical fields as well as in the health care industry.

Appendix A: Calculation of Position and Orientation

Provided that we know the physical configuration of the field generator (transmitter) which is fixed in position during operation, the magnetic field detected by a sensor is a function of the position and orientation of the sensor. In our system field generator coils are stimulated sequentially. The field sensed by a sensor (3 component sensors per probe) can be expressed in terms of position in x, y, z and orientation α, β, γ (roll, pitch and yaw respectively) i.e.:

B[sensor][coil] = f[sensor][coil](x, y, z, α, β, γ)

Where [sensor] designates a particular sensor and [coil] designates a particular transmitter coil.

If the real field the sensor measures when [coil] is on is B'[sensor][coil], then theoretically,

B'[sensor][coil] = B[sensor][coil]

i.e.

B'[sensor][coil] - f[sensor][coil](x, y, z, α, β, γ) = 0.0

Since we have 3 sensors and 3 coils, the total equations are 9 with 6 unknowns (x, y, z for probe space location, α, β, γ for its orientation). By applying non-linear least square method, we can find unique x, y, z, α, β, γ for the probe.

Above shows the general ideal of the algorithm. In detail:

Assume the orthogonal X,Y,Z reference coordinate system (magnetic location Cartesian coordinate) is described by matrix

$$e_l = \begin{bmatrix} e_{l11} & e_{l12} & e_{l13} \\ e_{l21} & e_{l22} & e_{l23} \\ e_{l31} & e_{l32} & e_{l33} \end{bmatrix}$$

the probe's orthogonal system is:

$$e_p = \begin{bmatrix} e_{p11} & e_{p12} & e_{p13} \\ e_{p21} & e_{p22} & e_{p23} \\ e_{p31} & e_{p32} & e_{p33} \end{bmatrix}$$

and, since the three sensors on probe may not be orthogonal to each other, their non-orthogonal axes can described as:

$$e_n = \begin{bmatrix} e_{n11} & e_{n12} & e_{n13} \\ e_{n21} & e_{n22} & e_{n23} \\ e_{n31} & e_{n32} & e_{n33} \end{bmatrix}$$

a transfer matrix T[i][j] which is to be used in later on calculation can be obtained from:

$$T_{[i][j]} = e_{n[i]} \bullet e_{p[j]}$$

$\forall i, j \in \{1,2,3\}$

another matrix ortho_OV[i][j] which is to be used also can be defined as:

$$ortho\_OV_{[i][j]} = e_{n[i]} \bullet e_{l[j]} \qquad \forall i, j \in \{1,2,3\}$$

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since we use roll(α), pitch(β), yaw(γ) to define probe orientation, ortho_OV[i][j] can be also described by:

5

$$\text{ortho\_OV[1][1]} = \cos(\alpha)\ \cos(\gamma) - \sin(\alpha)\ \sin(\beta)\ \sin(\gamma)$$

$$\text{ortho\_OV[1][2]} = \cos(\alpha)\ \sin(\gamma) - \sin(\alpha)\ \sin(\beta)\ \cos(\gamma)$$

10
$$\text{ortho\_OV[1][3]} = -\sin(\alpha)\ \cos(\beta)$$

$$\text{ortho\_OV[2][1]} = -\cos(\beta)\ \sin(\gamma)$$

$$\text{ortho\_OV[2][2]} = \cos(\beta)\ \cos(\gamma)$$

$$\text{ortho\_OV[2][3]} = \sin(\beta)$$

$$\text{ortho\_OV[3][1]} = \sin(\alpha)\ \cos(\gamma) + \cos(\alpha)\ \sin(\beta)\ \sin(\gamma)$$

15

$$\text{ortho\_OV[3][2]} = \sin(\alpha)\ \sin(\gamma) - \cos(\alpha)\ \sin(\beta)\ \cos(\gamma)$$

$$\text{ortho\_OV[3][3]} = \cos(\alpha)\ \cos(\beta)$$

20   orthogonal vector matrix can therefore be calculated by matrix multiplication of previous defined matrix T and orhto_OV:

$$ov = T * ortho\_OV$$

25

The theoretical magnetic field for an orthogonal system generated at sensor position pointing to $e_{T(i)}$ direction can be expressed as:

30      $$f[coil][i](x, y, z, \alpha, \beta, \gamma)$$

(detail abbreviated), where f is a known function, and includes a dipole moment term having magnitude proportional to the current flow in the particular coil.

After non_orthogonality correction (sensors may not be perpendicular to each other), the magnetic field sensor measures should be:

$$B[sensor][coil] = \sum_{i=1}^{3} f[coil][i](x,y,z,\alpha,\beta,\gamma) \times OV^{-1}[i][sensor]$$

Assume the real field sensor detected when coil is on is $B'[sensor][coil]$, then:

$$B'[sensor][coil] - B[sensor][coil] \approx 0.0$$

therefore, the 9 equations to be solved for x, y, z, α, β, γ, are:

$$B'[sensor1][coil1] - \sum_{i=1}^{3} f[coil1][i](x,y,z,\alpha,\beta,\gamma) \times OV^{-1}[i][sensor1] = 0.0$$

$$B'[sensor1][coil2] - \sum_{i=1}^{3} f[coil2][i](x,y,z,\alpha,\beta,\gamma) \times OV^{-1}[i][sensor1] = 0.0$$

$$B'[sensor1][coil3] - \sum_{i=1}^{3} f[coil3][i](x,y,z,\alpha,\beta,\gamma) \times OV^{-1}[i][sensor1] = 0.0$$

$$B'[sensor2][coil1] - \sum_{i=1}^{3} f[coil1][i](x,y,z,\alpha,\beta,\gamma) \times OV^{-1}[i][sensor2] = 0.0$$

$$B'[sensor2][coil2] - \sum_{i=1}^{3} f[coil2][i](x,y,z,\alpha,\beta,\gamma) \times_{OV}^{-1}[i][sensor2] \\ =0.0$$

$$B'[sensor2][coil3] - \sum_{i=1}^{3} f[coil3][i](x,y,z,\alpha,\beta,\gamma) \times_{OV}^{-1}[i][sensor2] = 0.0$$

5

$$B'[sensor3][coil1] - \sum_{i=1}^{3} f[coil1][i](x,y,z,\alpha,\beta,\gamma) \times_{OV}^{-1}[i][sensor3] = 0.0$$

$$B'[sensor3][coil2] - \sum_{i=1}^{3} f[coil2][i](x,y,z,\alpha,\beta,\gamma) \times_{OV}^{-1}[i][sensor3] = 0.0$$

10

$$B'[sensor3][coil3] - \sum_{i=1}^{3} f[coil3][i](x,y,z,\alpha,\beta,\gamma) \times_{OV}^{-1}[i][sensor3] = 0.0$$

A well-known non-linear least squares equation
15   solver can be applied to solve the above equations and
find probe position x, y, z and orientation α, β, γ.

Appendix B: Registration of Fiducial Markers

Assumption:

We know the coordinates of three fiducial points in image data (MR etc.) coordinate system (image position):

$$\{(Mx1,\ My1,\ Mz1),\ (Mx2,\ My2,\ Mz2),\ (Mx3,\ My3,\ Mz3)\}$$

and the coordinates of the same three fiducal points in the X,Y,Z, coordinate system of the fixed frame of reference of the magnetic locating apparatus:

$$\{(Px1,\ Py1,\ Pz1),\ (Px2,\ Py2,\ Pz2),\ (Px3,\ Py3,\ Pz3)\}$$

fiducial points $\{(x1,\ y1,\ z1),\ (x2,\ y2,\ z2),\ (x3,\ y3,\ z3)\}$ can be formed by $\{(a1,\ b1,\ c1),\ (a2,\ b2,\ c2),\ (a3,\ b3,\ c3)\}$ through rotation R and translation T. The rotation matrix R is:

$$R = \begin{bmatrix} Rxx & Ryx & Rzx \\ Rxy & Ryy & Rzy \\ Rxz & Ryz & Rzz \end{bmatrix}$$

where

$$Rxx = \cos(\alpha) \times \cos(\gamma) - \sin(\alpha) \times \sin(\beta) \times \sin(\gamma)$$

$$Rxy = \cos(\alpha) \times \sin(\gamma) + \sin(\alpha) \times \sin(\beta) \times \cos(\gamma)$$

$$Rxz = -\sin(\alpha) \times \cos(\beta)$$

$$Ryx = -\cos(\beta) \times \sin(\gamma)$$

$$Ryy = \cos(\beta) \times \cos(\gamma)$$

$$Ryz = \sin(\beta)$$

$$Rzx = \sin(\alpha) \times \cos(\gamma) + \cos(\alpha) \times \sin(\beta) \times \sin(\gamma)$$

$$Rzy = \sin(\alpha) \times \sin(\gamma) - \cos(\alpha) \times \sin(\beta) \times \cos(\gamma)$$

$$Rzz = \cos(\alpha) \times \cos(\beta)$$

The translation matrix T is:

$$T = \begin{bmatrix} x & y & z \\ x & y & z \\ x & y & z \end{bmatrix}$$

5

The relationship between image position and magnetic location apparatus frame of reference position is:

10

$$\begin{bmatrix} Mx1 & My1 & Mz1 \\ Mx2 & My2 & Mz2 \\ Mx3 & My3 & Mz3 \end{bmatrix} R + T = \begin{bmatrix} Px1 & Py1 & Pz1 \\ Px2 & Py2 & Pz2 \\ Px3 & Py3 & Pz3 \end{bmatrix}$$

or

$$\begin{bmatrix} Mx1 & My1 & Mz1 \\ Mx2 & My2 & Mz2 \\ Mx3 & My3 & Mz3 \end{bmatrix} R + T - \begin{bmatrix} Px1 & Py1 & Pz1 \\ Px2 & Py2 & Pz2 \\ Px3 & Py3 & Pz3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

15

This forms 9 single equations:

$$Mx1 \times Rxx + My1 \times Rxy + Mz1 \times Rxz + x - Px1 = 0$$
$$Mx1 \times Ryx + My1 \times Ryy + Mz1 \times Ryz + y - Py1 = 0$$
$$Mx1 \times Rzx + My1 \times Rzy + Mz1 \times Rzz + z - Pz1 = 0$$
$$Mx2 \times Rxx + My2 \times Rxy + Mz2 \times Rxz + x - Px2 = 0$$
$$Mx2 \times Ryx + My2 \times Ryy + Mz2 \times Ryz + y - Py2 = 0$$
$$Mx2 \times Rzx + My2 \times Rzy + Mz2 \times Rzz + z - Pz2 = 0$$
$$Mx3 \times Rxx + My3 \times Rxy + Mz3 \times Rxz + x - Px3 = 0$$
$$Mx3 \times Ryx + My3 \times Ryy + Mz3 \times Ryz + y - Py3 = 0$$
$$Mx3 \times Rzx + My3 \times Rzy + Mz3 \times Rzz + z - Pz3 = 0$$

........(*)

with 6 unknowns: α, β, γ for rotation angles, x, y, z for space translation.

The registration procedure is to find rotation angles α, β, γ and space translation x, y, z by solving the above 9 equations.

In pseudo-code, the registration procedure is:

```
registration()
{
        Initialize data buffer;
        Assign fiducial reference points to image
data (usually 3 points);
        Initialize magnetic locating system;
        Measure  lab  positions  of  the  chosen
fiducial points;
        Apply equation solving method (non-linear
least square) on equations(*),
                and find rotation angles α, β, γ and
space translation x, y, z;
        Form rotation matrix R from α, β, γ and
translation matrix T from x, y, z;
        }
```

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The rotation matrix R and translation matrix T can be applied to subsequent positions obtained, including the positions of the of the sensor associated with the catheter.

5

CLAIMS:

1.   Apparatus   for   determining   position
comprising:

(a) field generating means (10) for
producing a plurality of magnetic fields, each said
field having parameters varying with location within a
sensing volume (50) according to a known pattern of
variation, said patterns of variation being different
for different ones of said fields;

(b) at least one sensor (18) adapted to
detect one or more of said parameters prevailing at such
sensor when said sensor is at an unknown location within
said sensing volume and to provide one or more sensor
signals representing said one or more parameters;

(c) calculation means (32) for
determining a calculated location of said sensor based
upon said sensor signals and said known patterns of
variation; and

(d) feedback control means (34) for
adjusting said field generating means to alter said
known pattern of variation of at least one of said
fields responsive to said sensor signals, said
calculated location or both so as to maintain said
parameters of each such altered field prevailing at said
sensor within a preselected range.

2.   Apparatus for determining position
comprising:

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(a) a plurality of sensors (110) adapted to detect one or more parameters of a magnetic field prevailing at each such sensor and to provide one or more sensor signals representing said one or more
5   parameters, said sensors being disposed adjacent a sensing volume (150) at different positions, different orientations or both;

(b) field generating means including at least one magnetic field transmitter (118) movable to an
10   unknown location within said sensing volume and adapted to provide at least one magnetic field in said sensing volume, so that the magnetic field from each transmitter varies in according to a known pattern of variation with location relative to such transmitter whereby said
15   sensor signals will represent one or more parameters of the field or fields from said at least one transmitter;

(c) calculation means (32) for determining a calculated location of said at least one transmitter based upon said sensor signals and said
20   known patterns of variation; and

(d) feedback control means (34) for adjusting said field generating means to alter said known pattern of variation of at least one of said fields responsive to said sensor signals, said
25   calculated location or both so as to maintain said parameters of each such altered field prevailing at each said sensor within a preselected range.

3. Apparatus as claimed in claim 1 or claim 2 wherein said field generating means is operative to provide DC magnetic fields within said sensing volume.

4. Apparatus as claimed in claim 3 wherein said field generating means includes a plurality of coils (10, 120, 122, 124) and means for intermittently actuating each said coil (34, 42, 44, 46) with a direct current, said feedback control means includes means for altering the magnitude of each said direct current, and wherein said calculation means includes means for sampling the signals from each sensor when a delay time has elapsed after commencement of each said intermittent actuation, said feedback control means further including means for varying the delay time for each actuation in accordance with the magnitude of the current applied in such actuation so as to reduce the delay time when lesser currents are employed and increase the delay time when greater currents are employed.

5. Apparatus as claimed in claim 1 or claim 2 wherein said field generating means is operative to provide AC magnetic fields within said sensing volume.

6. Apparatus as claimed in claim 1 or claim 2 wherein each said sensor has maximum accuracy within a preselected optimum operational range for each said parameter and said preselected range for each said parameter substantially corresponds to said optimum operational range.

7. Apparatus as claimed in claim 1 or claim 2 wherein said preselected range for each said parameter

consists of a single value, and wherein said feedback control means is operative to maintain each said parameter of the field at each sensor substantially at said single value.

8.   Apparatus as claimed in claim 1 wherein said field generating means includes a plurality of transmitters (10) disposed adjacent said sensing volume.

9.   Apparatus as claimed in claim 2 or claim 8 wherein each said transmitter is operative to radiate a field having magnitude decreasing with r^n where r is distance from the transmitter and n is a number greater than 1.

10.   Apparatus as claimed in claim 9 wherein each said transmitter is operative to radiate a field having magnitude substantially equal to K/r^3 where K is a real number, and wherein said feedback control means is operative to adjust K.

11.   Apparatus as claimed in claim 1 further comprising a sensor body (18), said at least one sensor including a plurality of component sensors (20, 22, 24) disposed on said sensor body, each said component sensor being operative to measure the magnitude of a magnetic field component in a preselected local direction relative to the sensor body.

12.   Apparatus as claimed in claim 11 wherein said field generating means includes a plurality of transmitters (10) disposed at spaced-apart locations adjacent said sensing volume, said feedback control means being operative to adjust each said transmitter to

transmit a plurality of fields so that for each said field, the magnitude of a component of such field in the local direction of one said component sensor will be within a preselected range.

13. Apparatus as claimed in claim 11 wherein each said component sensor is a Hall effect sensor, a magnetoresistive sensor, a magnetooptical sensor or a flux gate magnetometer.

14. Apparatus as claimed in claim 1 or claim 2 wherein each said sensor includes a coil and wherein said field generating means is arranged to provide AC fields in said sensing volume.

15. Apparatus as claimed in claim 1 wherein said field generating means includes a plurality of transmitters disposed at spaced-apart locations on one side of a reference plane and wherein said sensing volume extends to the other side of said reference plane.

16. Apparatus as claimed in claim 15 wherein said transmitters are disposed substantially in a common plane.

17. Apparatus as claimed in claim 2 wherein said plurality of sensors are disposed at spaced-apart locations on one side of a reference plane and wherein said sensing volume extends to the other side of said reference plane.

18. Apparatus as claimed in claim 17 wherein said sensors are disposed substantially in a common plane.

19. Apparatus as claimed in claim 1 or claim 2 wherein said at least one sensor includes a plurality of sensors, and wherein said sensors can be impaired by exposure to fields having components above a predetermined threshold magnitude, and wherein said feedback control means includes means for controlling said field generating means to assure that no sensor is exposed to a field component having magnitude above its threshold value.

20. Apparatus as claimed in claim 1 or claim 2 wherein said at least one sensor includes a plurality of sensors and wherein said sensors can be impaired by exposure to fields having components above a predetermined threshold magnitude but can be restored after such exposure upon application of a reset routine, said feedback control means including means for initiating such reset routine in the event of such exposure.

21. Apparatus for sensing the disposition of an object in a frame of reference comprising:

(a) transmitter means (10) including at least one transmitter for providing a field;

(b) sensor means (18) including at least one sensor for sensing one or more parameters of a field prevailing at each such sensor and providing one or more sensor signals indicative of such parameters, said transmitter means and said sensor means cooperatively defining a plurality of transmitter-sensor pairs, each including one transmitter and one sensor as elements of

the pair, one element of each such pair being disposed on the object and the other element of each such pair being disposed at a known disposition in said frame of reference;

5   (c)   calculation   means   (32)   for determining the disposition of said object in said frame of reference based upon said sensor signals; and

            (d) feedback control means (34) for adjusting said transmitting means responsive to said

10 sensor signals to thereby maintain at least one of said sensor signals within a preselected range.

22. A method of determining the disposition of an object in a frame of reference comprising the steps of:

15   (a) providing one or more magnetic fields each having a known pattern of variation with respect to said frame of reference;

          (b) sensing one or more parameters of said one or more magnetic fields prevailing at said

20 object to provide one or more sensor signals indicative of said one or more parameters;

          (c) calculating the disposition of said object in said frame of reference based upon said sensor signals and said known pattern or patterns of variation;

25 and

          (d) altering said known pattern of variation of at least one of said one or more magnetic fields responsive to said sensor signals, said calculated disposition or both so as to maintain said

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parameters of each such altered field prevailing at said object within a preselected range.

23. A method of determining the disposition of an object in a frame of reference comprising the steps of:

(a) providing one or more magnetic fields each having a known pattern of variation in space with respect to object;

(b) sensing one or more parameters of said one or more magnetic fields prevailing at one or more sensors having known disposition in said frame of reference to provide one or more sensor signals indicative of said one or more parameters;

(c) calculating the disposition of said object in said frame of reference based upon said sensor signals and said known pattern or patterns of variation of said one or more magnetic fields; and

(d) altering said known pattern of variation of at least one of said one or more magnetic fields responsive to said sensor signals, said calculated disposition or both so as to maintain said parameters of each such altered field prevailing at at least one of said sensors within a preselected range.
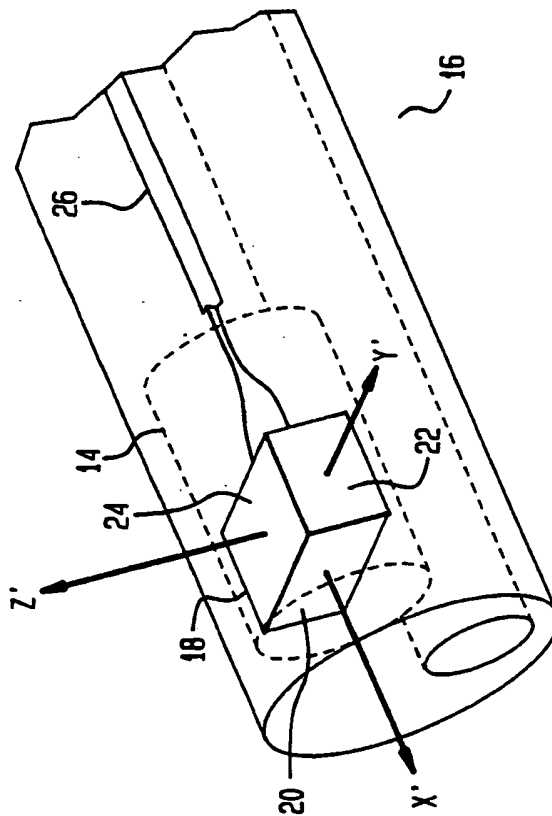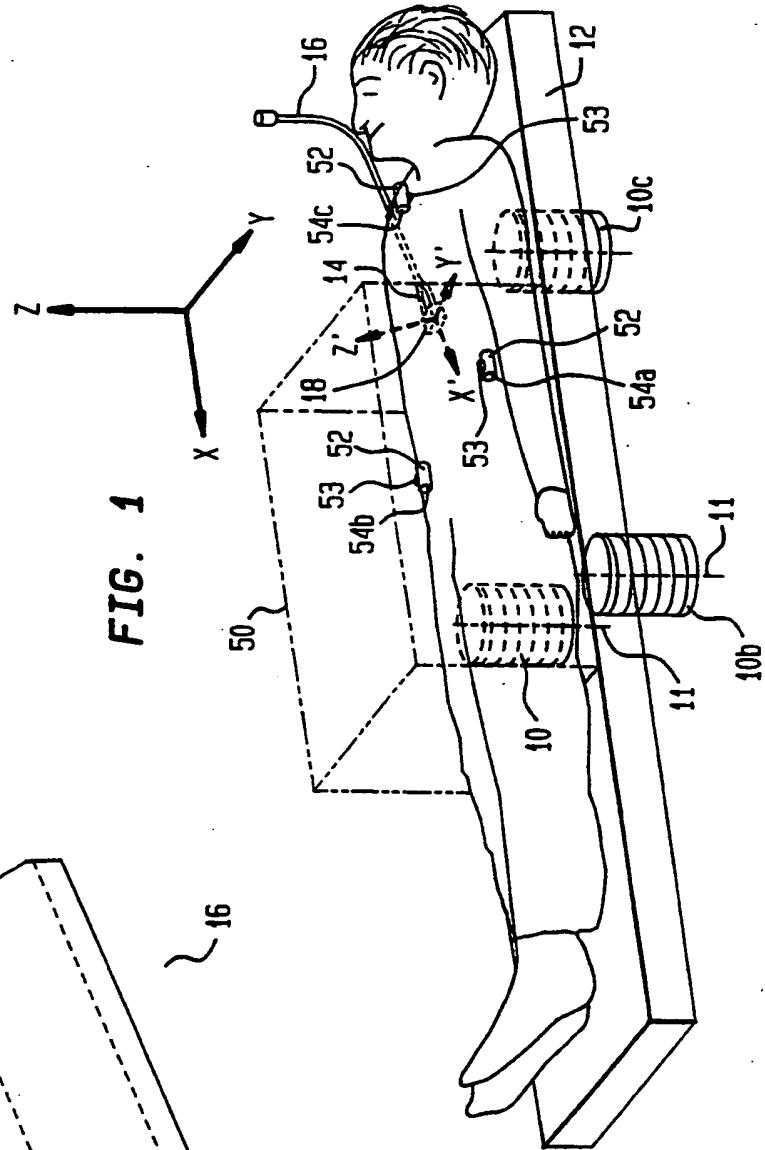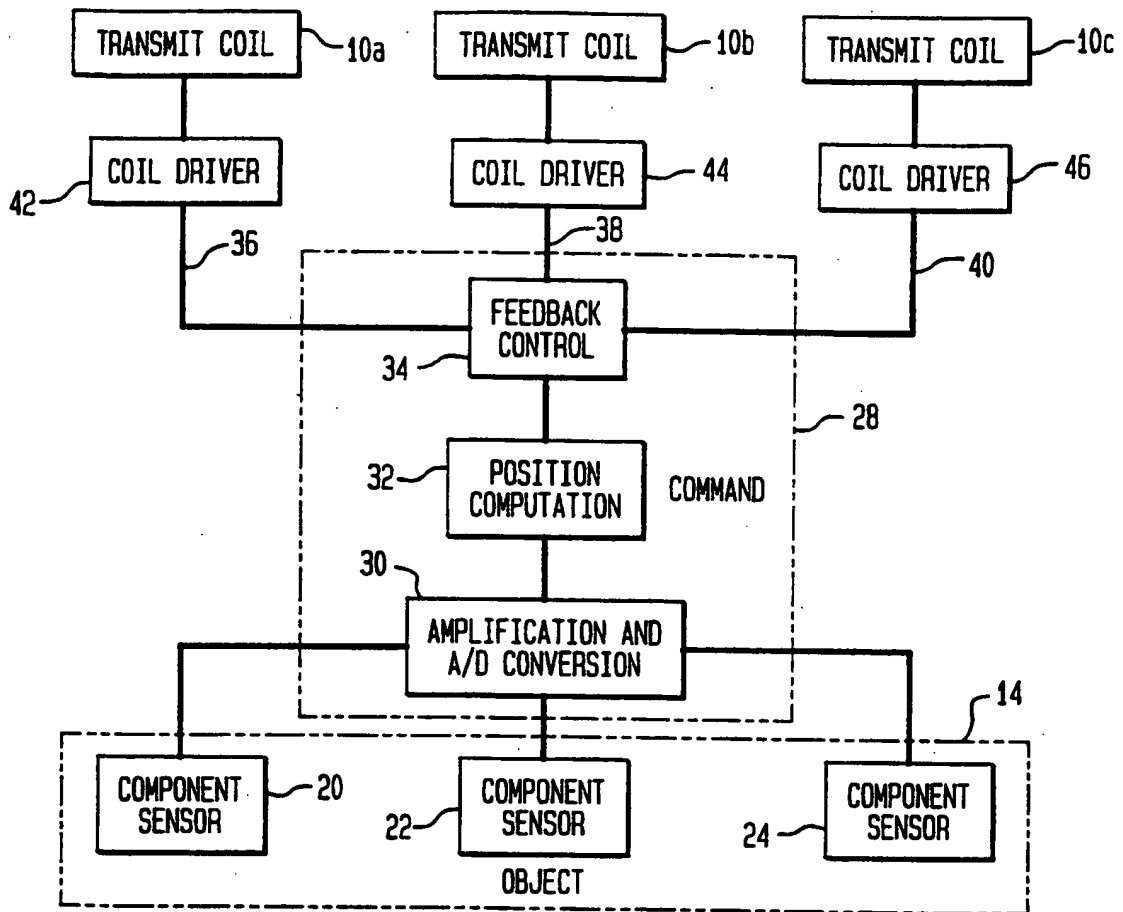
FIG. 1

FIG. 2

FIG. 3

```
┌──────────────┐        ┌──────────────┐        ┌──────────────┐
│ TRANSMIT COIL│──10a   │ TRANSMIT COIL│──10b   │ TRANSMIT COIL│──10c
└──────────────┘        └──────────────┘        └──────────────┘
        │                       │                       │
┌──────────────┐        ┌──────────────┐        ┌──────────────┐
│ COIL DRIVER  │        │ COIL DRIVER  │──44    │ COIL DRIVER  │──46
└──────────────┘        └──────────────┘        └──────────────┘
42            36                 38                      40
                ┌──────────────┐
                │   FEEDBACK   │
                │   CONTROL    │
                └──────────────┘
              34                              28
                ┌──────────────┐
           32───│   POSITION   │   COMMAND
                │ COMPUTATION  │
                └──────────────┘
           30
                ┌──────────────┐
                │AMPLIFICATION │
                │AND A/D       │
                │CONVERSION    │
                └──────────────┘
                                                  14
┌──────────────┐    ┌──────────────┐    ┌──────────────┐
│  COMPONENT   │─20 │  COMPONENT   │    │  COMPONENT   │
│   SENSOR     │    │   SENSOR     │    │   SENSOR     │
└──────────────┘  22└──────────────┘ 24 └──────────────┘
                      OBJECT
```
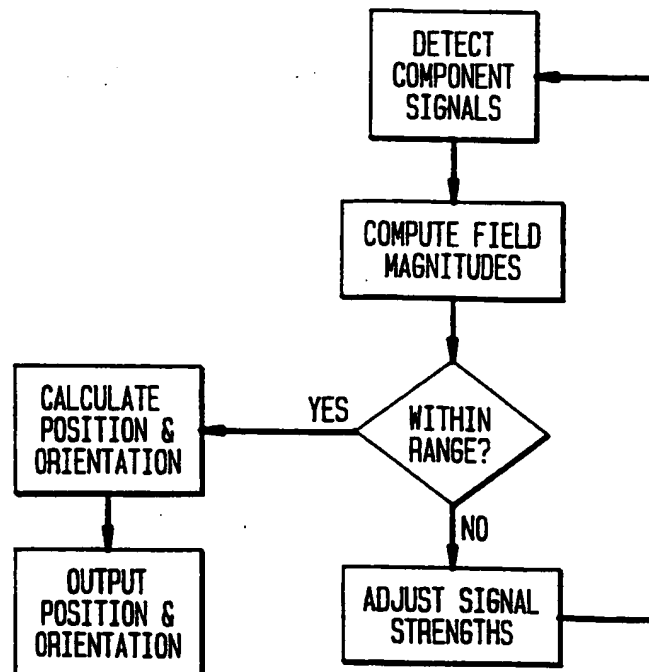
FIG. 4

```
              ┌──────────────┐
              │   DETECT     │
              │  COMPONENT   │◄─────────┐
              │   SIGNALS    │          │
              └──────────────┘          │
                     │                  │
              ┌──────────────┐          │
              │ COMPUTE FIELD│          │
              │  MAGNITUDES  │          │
              └──────────────┘          │
                     │                  │
┌──────────────┐    ╱╲                  │
│  CALCULATE   │   ╱  ╲                 │
│  POSITION &  │◄─╱WITHIN╲              │
│ ORIENTATION  │YES╲RANGE?╱             │
└──────────────┘   ╲    ╱               │
       │            ╲  ╱                │
       │             ╲╱                 │
       │              │NO               │
┌──────────────┐    ┌──────────────┐    │
│   OUTPUT     │    │ADJUST SIGNAL │    │
│  POSITION &  │    │ STRENGTHS    │────┘
│ ORIENTATION  │    └──────────────┘
└──────────────┘
```
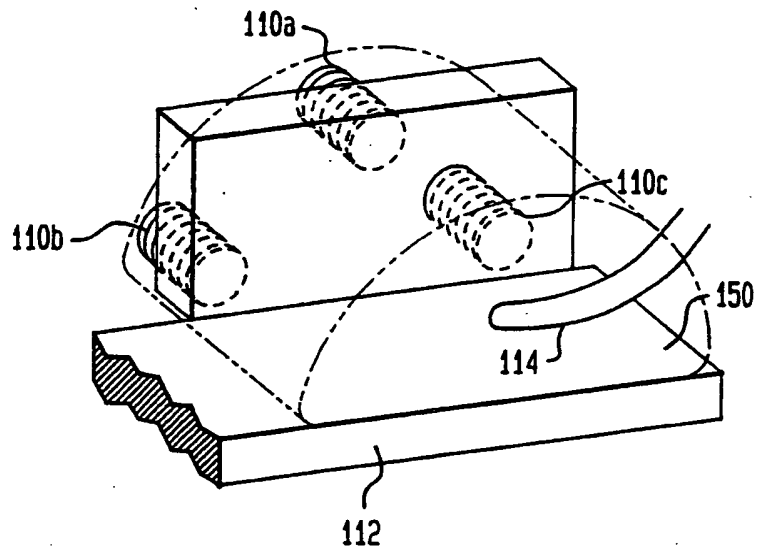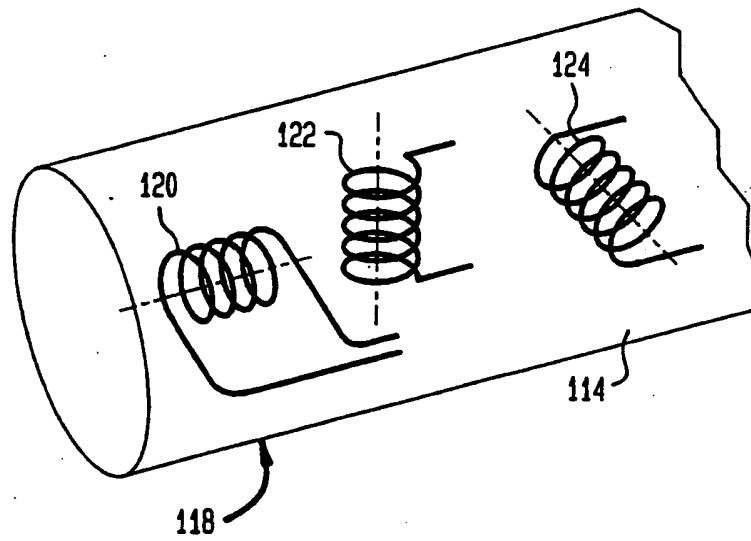
FIG. 5

FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/08411

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : G01B 7/14
US CL :324/207.12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 324/207.12, 207.15, 207.16, 207.17, 207.22, 225, 232

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X ---- Y	US, A, 4,652,820 (MARESCA) 24 MARCH 1987 col. 3, lines 18-34	1,5/1,6/1,7/1,1 4/1,22 and 23 --------------- 2,3,5/2, 6/2,7/2, 9,11,13, 14/2,15-18 and 21

☐ Further documents are listed in the continuation of Box C.   ☐ See patent family annex.

Date of the actual completion of the international search	Date of mailing of the international search report
12 JULY 1996	30 SEP 1996
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	Authorized officer WALTER E. SNOW
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